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Demodulation of DPSK Signals up to 40 Gb/s Using a Highly Birefringent Photonic Bandgap Fiber

Christophe Peucheret, Yan Geng, Beáta Zsigri, Thomas Tanggaard Alkeskjold, Theis Peter Hansen, and Palle Jeppesen

Abstract—Phase-to-intensity modulation conversion of differential phase-shift keying signals is successfully demonstrated at 10 and 40 Gb/s using a polarization Mach–Zehnder delay interferometer implemented with only 2.4 m of a highly birefringent air-guiding photonic bandgap (PBG) fiber. Such a PBG fiber exhibits a birefringence one order of magnitude larger than that of conventional polarization-maintaining fibers, thus enabling the realization of compact interferometers. Furthermore, its single material nature is expected to result in reduced temperature sensitivity.

Index Terms—Delay interferometer (DI), differential phase-shift keying (DPSK), photonic bandgap (PBG) fiber, polarization interferometer.

I. INTRODUCTION

DIFFERENTIAL phase-shift keying (DPSK) has emerged as a promising technology for future high-capacity optical communication systems due to its robustness to transmission impairments and improved receiver sensitivity over ON–OFF keying offered by balanced detection [1]. In order to make DPSK compatible with direct detection systems, a demodulator is needed to realize phase-to-intensity modulation conversion at the receiver. This is usually performed using a 1-bit delay interferometer (DI) whose output power depends on the relative phase between two consecutive bits. Phase-to-intensity modulation conversion at the transmitter side has also been suggested as a method to generate return-to-zero (RZ) modulation formats whose duty cycle can be tailored by a proper choice of the interferometer delay [2].

DIs are customarily based on the Mach–Zehnder configuration and are commonly implemented in all-fiber structures or as planar lightwave circuits (PLCs). Alternatively, Michelson interferometer structures have also been reported, either based on free-space optics [3], or using a PLC coupler with Bragg reflectors [4]. In order to be used as DPSK demodulators, 1-bit DIs should satisfy a number of practical requirements, including compactness, compatibility with optical fibers, polarization independence, as well as thermal and mechanical stability.

An equivalent Mach–Zehnder structure that exploits the birefringence of polarization-maintaining (PM) fibers to realize the

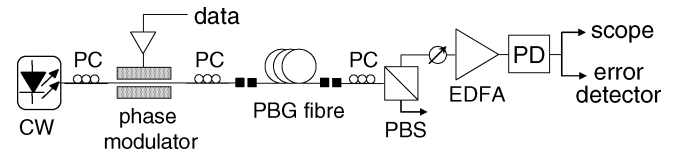


Fig. 1. Experimental setup. CW: continuous-wave laser. PC: polarization controller. EDFA: erbium-doped fiber amplifier. PD: photodiode.

required delay between light contributions propagating along its two eigen-axes has been recently demonstrated [5]. Typical birefringence values associated with conventional commercially available PM fibers (of the order of 2 to 5×10^{-4}) mean that fiber lengths over 15 m are required to achieve the 25-ps delay necessary to demodulate a 40-Gb/s signal. Furthermore, conventional PM fibers rely on stress-induced birefringence that is realized in practice by adding two borosilicate rods on both sides of the core. However, the stress-applying rods and the surrounding silica cladding have different thermal expansion coefficients, resulting in temperature sensitive operation of a DI based on such principle.

Microstructured fibers have been shown to offer additional design degrees of freedom enabling tailoring of their polarization properties. In particular, the polarization properties of photonic bandgap (PBG) fibers where light propagates in a low refractive index core surrounded by a high effective index microstructured cladding [6] have recently started being the object of attention [7], [8].

In this letter, we report the use of a short piece of PBG fiber (2.4 m) to perform phase-to-intensity modulation conversion of DPSK signals at 10 and 40 Gb/s. The fiber birefringence is one order of magnitude larger than that of typical PM fibers, enabling a compact and stable device to be implemented. The fiber is also single material, which is expected to result in a reduced temperature sensitivity of the DI.

II. EXPERIMENTAL RESULTS

The experimental setup is represented in Fig. 1. Continuous-wave light from a tunable external cavity laser is phase modulated with ideally π phase shifts using a phase modulator suitable for operation up to 40 Gb/s, resulting in a constant intensity DPSK signal. The state of polarization of the modulated light is rotated using a polarization controller, so that it couples equally to the two eigen-axes of the PBG fiber. Due to birefringence, some delay is accumulated between the two eigen-polarizations over propagation in the fiber. At the PBG fiber output, a polarization beam splitter (PBS) is used so that the two orthogonal contributions interfere. An extra polarization controller is used

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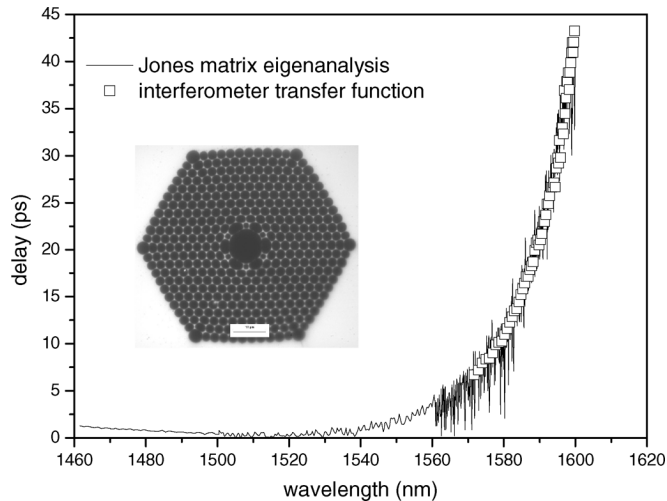


Fig. 2. Delay of the interferometer as a function of wavelength measured using Jones matrix eigenanalysis and calculated from the periodicity of the measured interferometer transfer function. The inset shows the fiber cross section.

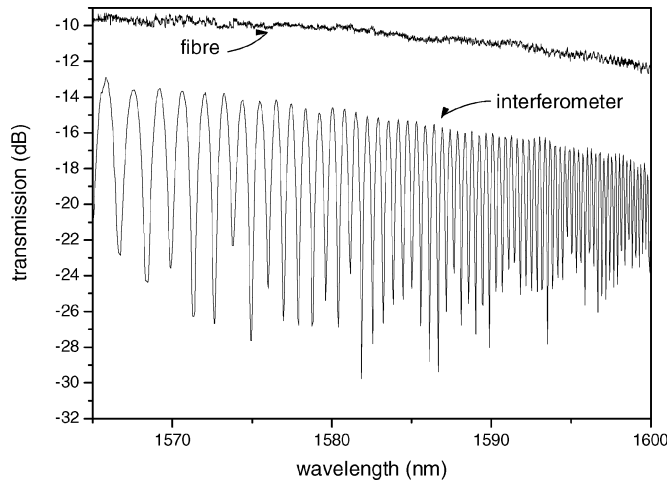


Fig. 3. Transmission of the 2.4-m PBG fiber and of the polarization interferometer. The insertion losses of two polarization controllers and one PBS are further included in the values reported for the interferometer.

to rotate the two orthogonal states of polarization to 45° of the axes of the PBS. One of the PBS outputs is then input to a preamplified receiver consisting of an *L*-band erbium-doped fiber amplifier and a 50-GHz photodiode.

The PBG fiber used in the experiment is 2.4 m long and its structure is represented as an inset in Fig. 2 [9]. The 3-dB bandwidth of its bandgap extends up to 1600 nm, as shown in Fig. 3, and the loss per unit length of the fiber is estimated to 88 dB/km in the bandgap [7], resulting in a loss of about 0.2 dB for the 2.4-m sample used in the experiment. In our implementation, the total loss is mostly due to the use of butt coupling to and from standard single-mode fibers. However, it has been shown in [9] that such coupling loss could be minimized by proper splicing and values of 1 dB per splice can be achieved. The transfer function of the DI was measured under polarized white light illumination and is also represented in Fig. 3. The variations of the differential group delay with wavelength were extracted from the periodicity of the interferometer transfer function and are represented in Fig. 2, together with results of measurements per-

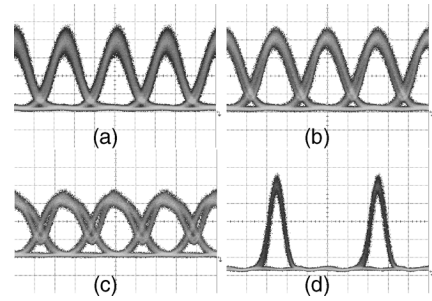


Fig. 4. Eye diagrams for 39.8-Gb/s operation at (a) 1580 nm, (b) 1585 nm, (c) 1591 nm, and (d) for 9.95-Gb/s operation at 1580 nm. Horizontal scales: (a)–(c) 10, (d) 20 ps/div.

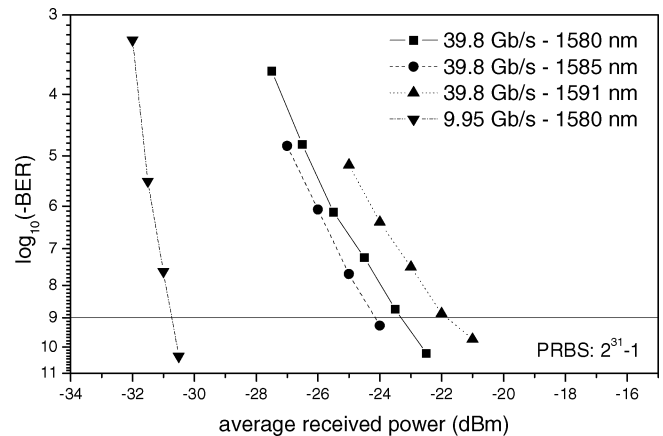


Fig. 5. Measured BER curves at the DI output for various wavelengths at 39.8 and 9.95 Gb/s.

formed using Jones matrix eigenanalysis [10], showing excellent agreement. The delay is seen to increase significantly at the edge of the fiber bandgap. A value of 25 ps suitable for demodulation of a 40-Gb/s DPSK signal is reached at 1592 nm. This corresponds to a birefringence of 3.1×10^{-3} , which is about one order of magnitude larger than for conventional PM fibers (beat lengths in the range $3.0 \leq L_B \leq 5.0$ mm at 1550 nm, resulting in birefringence $3.1 \times 10^{-4} \leq \Delta n \leq 5.2 \times 10^{-4}$ are typical values for commercially available PM fibers).

A DPSK modulated signal at 39.8 Gb/s was input to the DI while the output signal was monitored. The output eye diagrams are represented for selected wavelengths in Fig. 4(a)–(c). The pulsewidth increases with increasing wavelength, as expected from the delay variations. For 9.95-Gb/s operation [Fig. 4(d)], a small duty cycle pulse is obtained at the interferometer output, due to the short interferometer delay compared to the 100-ps bit slot.

Bit-error-rate curves corresponding to the eye diagrams of Fig. 4 are shown in Fig. 5 for a pseudorandom sequence length of $2^{31} - 1$. A sensitivity of -23.3 dBm is obtained at 1580 nm at 39.8 Gb/s. This relatively poor sensitivity is partly attributed to the use of a phase modulator for generation of the DPSK signal, resulting in inexact π phase shifts. Note that, for delays smaller than the bit duration, the experimental configuration of Fig. 1 effectively corresponds to an RZ transmitter followed by a preamplified receiver, for which sensitivity improvements due to impulse coding are expected [11], as indeed observed for shorter

wavelengths. However, local variations in the bandgap transmission and interferometer extinction ratio could result in slightly enhanced pulse quality at some wavelengths, as observed at 1585 nm. As a comparison, an improved receiver sensitivity of -30.7 dBm was measured at 1580 nm for 9.95-Gb/s operation due to the reduced bit rate and lower pulse duty cycle.

III. DISCUSSION

Polarization-insensitive operation for birefringent interferometers has previously been demonstrated using Sagnac loop configurations [12], [13]. Furthermore, the type of PBG fiber used in this experiment has been shown to be insensitive to bending loss away from the short wavelength edge of the bandgap. Bending diameters down to 10 mm have been demonstrated [9], thus enabling the realization of compact devices. The proposed DI exploits the large birefringence of the PBG fiber at the edge of its bandgap and is, therefore, not tunable in wavelength, which would constitute a drawback compared to conventional Mach-Zehnder structures where thermal phase tuning can be achieved. Operation at a desired wavelength can be achieved by proper length adjustment, provided the wavelength is at the bandgap edge, or by scaling of the PBG structure, which would result in a shift of the bandgap.

Being single material fiber, it should not suffer from the temperature-induced polarization changes due to the different thermal expansion coefficients of the cladding and the stress-applying rods used in conventional PM fibers. Temperature-insensitive Sagnac interferometers have been demonstrated using solid core photonic crystal fibers [14], [15] and the low-temperature dependence of the birefringence of PBG fibers has also been confirmed experimentally [7]. Finally, the fiber design can be optimized further in order to achieve even larger values of form birefringence [16], [17].

Consequently, practical realizations of compact, temperature and polarization insensitive DIs relying on the high birefringence of PBG fibers should be possible.

IV. CONCLUSION

We have demonstrated phase-to-intensity modulation conversion of 10- and 40-Gb/s DPSK signals using a polarization DI making use of only 2.4 m of air-guiding PBG fiber. The fiber length reduction is made possible by the high birefringence of the PBG fiber used in our experiment, which is one order of magnitude larger than that of conventional PM fibers. The use of such fibers opens the way for compact and temperature stable implementations of DIs for DPSK demodulation at the receiver side, or RZ signal generation at the transmitter side.

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